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**"Strain Buildup and Release, Earthquake Prediction
and Selection of VBL Sites for Margins of the North Pacific"**

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SUMMARY

During the past year, the grant supported research on several aspects of crustal deformation. The relation between earthquake displacements and fault dimensions was studied in an effort to find scaling laws that relate static parameters such as slip and stress drop to the dimensions of the rupture. Several implications of the static relations for the dynamic properties of earthquakes such as rupture velocity and dynamic stress drop were proposed.

A theoretical basis for earthquake-related phenomena associated with slow rupture growth or propagation, such as delayed multiple events, was developed using the stress intensity factor defined in fracture mechanics and experimental evidence from studies of crack growth by stress corrosion.

Finally, extensive studies by Japanese geologists have established the offset across numerous faults in Japan over the last one hundred thousand years. These observations of intraplate faulting are being used to establish the spatial variations of the average strain rate of subregions in southern Japan. Historic intraplate seismicity has also been interpreted as a regional strain pattern for comparison with the long-term geologic pattern. The historic seismic data were used to establish a relation between the length of a fault and the maximum size earthquake possible on the fault. The geologically observed slip rate then was combined with the observed size distribution of earthquakes (b-value) to predict repeat times between intervals of different intensity ground shaking, or one form of seismic risk map.

COMPLETED RESEARCH

Scaling Laws for Large Earthquakes

It is observed that the mean slip in large earthquakes correlates linearly with fault length L and is not simply related to fault width, W . If we interpret this in terms of an elastic model, it implies that static stress drop increases with aspect ratio (L/W). We also observe a tendency, both for strike-slip and thrust earthquakes, for aspect ratio, and hence static stress drop, to increase with seismic moment. Dynamic models of rupture of a rectangular fault in an elastic medium show that the final slip should be controlled by the fault width and scale with the dynamic stress drop. The only way these models can be reconciled with the observations is if dynamic stress drop correlates with fault length so that it is also nearly proportional to aspect ratio. This could only happen if fault length is determined by the dynamic stress drop. There are several serious objections to this, which lead us to suspect that these models may be poor representations of large earthquakes. Firstly, it conflicts with the observations for small earthquakes (modeled as circular sources) that stress drop is nearly constant and independent of source radius. Secondly, it conflicts with the observation that fault length is often determined by the size of seismic gap in which the earthquake occurred. We speculate that the boundary condition at the base of the fault, that slip is zero, is unrealistic because that edge is in a ductile region at the base of the seismogenic layer. In a model in which slip is not so

constrained at the base of the fault nor at the top (the free surface), such that no healing wave originates from these edges, final slip would be determined by fault length. The observations would then be interpreted as meaning that the static and dynamic stress drops of large earthquakes are nearly constant. Geodetic data for the 1906 San Francisco earthquake show that this model is not satisfactory, either. These two extreme models predict very different scaling of the dynamics of large earthquakes. The width-dependent model predicts that average particle velocities are larger for long ruptures but the rise time will be the same as in a shorter event of the same width. The length-dependent model predicts the opposite.

Time-Dependent Rupture

Using the concepts of fracture mechanics, we develop a theory of the earthquake mechanism which includes the phenomenon of subcritical crack growth. The theory specifically predicts the following phenomena: slow earthquakes, multiple events, delayed multiple events (doublets), postseismic rupture growth and afterslip, foreshocks, and aftershocks. The theory also predicts that there must be a nucleation stage prior to an earthquake, and suggests a physical mechanism by which one earthquake may 'trigger' another.

These predictions are obtained by combining two fundamental concepts. The first is that

$$k = C \Delta \tau \sqrt{x}$$

and the second, that

$$k = K_0 \left(\frac{\dot{X}}{V_0} \right)^{1/n}$$

where k is the stress intensity factor, $\Delta\tau$ stress drop, X rupture length, \dot{X} rupture velocity, C a geometrical factor, and K_0 , V_0 , and n are material constants. The first is a fundamental result of fracture mechanics; the second describes stress corrosion cracking, a well-established physical process.

We investigate in detail two phenomena of special interest and which are not predicted by ordinary fracture mechanics: nucleation and delayed multiple events. In the first case, we find that all earthquakes must be preceded by quasistatic slip over a portion of their rupture surfaces, but it may be difficult to detect in practice. In the second case, we studied two pairs of delayed multiple events that were separated by the same 'barrier' in order to calculate K_0 and n . The results are that the stress corrosion index, $n \approx 24$ and the stress corrosion limit, $10^4 < K_0 < 10^6$ bars $\text{km}^{1/2}$. The latter uncertainty is due to uncertainty in V_0 , which we assume to be in the range $10^{-10} < V_0 < 10^{-3}$ km/hr.

Japanese Intraplate Crustal Deformation

The historical record of large ($M \geq 6.9$) earthquakes and geologically determined rates of slip on Quaternary faults in intraplate Japan (Honshu and Shikoku) are used to estimate the average rate of seismic moment-release (\dot{M}_{ij}) for the last 400 years and during the late Quaternary, respectively. Values of \dot{M}_{ij} estimated from the two data sets are nearly equivalent in regions where seismic activity is concentrated on land. This observation suggests that \dot{M}_{ij} in intraplate Japan has been constant during the late Quaternary and is relatively free from secular variation when averaged over periods of several hundreds of years. The fabric of Quaternary faults in northeast Japan indicates that the principal axis of horizontal compression is oriented eastward, parallel to the relative plate velocity between the Eurasian and Pacific plates along the Japan trench. Similarly, the pattern of Quaternary faulting in Shikoku shows a compressive stress field that trends northwest approximately parallel to the relative plate velocity vector between the Eurasian and Philippine Sea plates along the Nankai trough. The mode of intraplate deformation in Shikoku is, however, in marked contrast to that observed in northeast Honshu. Virtually all \dot{M}_{ij} in Shikoku may be attributed to slip along one fault, the Median Tectonic Line (MTL). In contrast, \dot{M}_{ij} in northeast Honshu is divided among a regional set of reverse-type faults that strike northerly, perpendicular to the direction of plate subduction along the Japan trench. The easterly strike of the MTL is consistent with the idea that oblique plate subduction along the

Nankai trough is partially accommodated by right-lateral motion along the MTL. Conversion of \dot{M}_{ij} in northeast Japan to strain-rates ($\dot{\epsilon}_{ij}$) suggests that about 3 to 9% of the relative plate motion between Japan and the Pacific plate (≈ 9.7 cm/year) is accommodated as a permanent eastward shortening (3-9 mm/yr) of intraplate Japan.

Figure 1. Regional averages of the rates of moment-release, horizontal compressive strain and crustal shortening calculated from the 400 year record of seismicity. Principal directions of horizontal compressive strain and shortening are denoted by dashed bars. Note that the values in the Izu region are calculated from seismicity within the small dashed box that encloses the Izu Peninsula.

Figure 2. Regional and grid-by-grid averages of the rates of moment-release, horizontal compressive strain, and crustal shortening calculated from geologically determined slip-rates of Quaternary faults. Principal directions of horizontal compressive strain for the larger intraplate regions and smaller grids are shown by dashed bars and thin solid lines, respectively. Smaller numerals within the region of central Japan give average rates for the local areas enclosed by the dashed boxes.

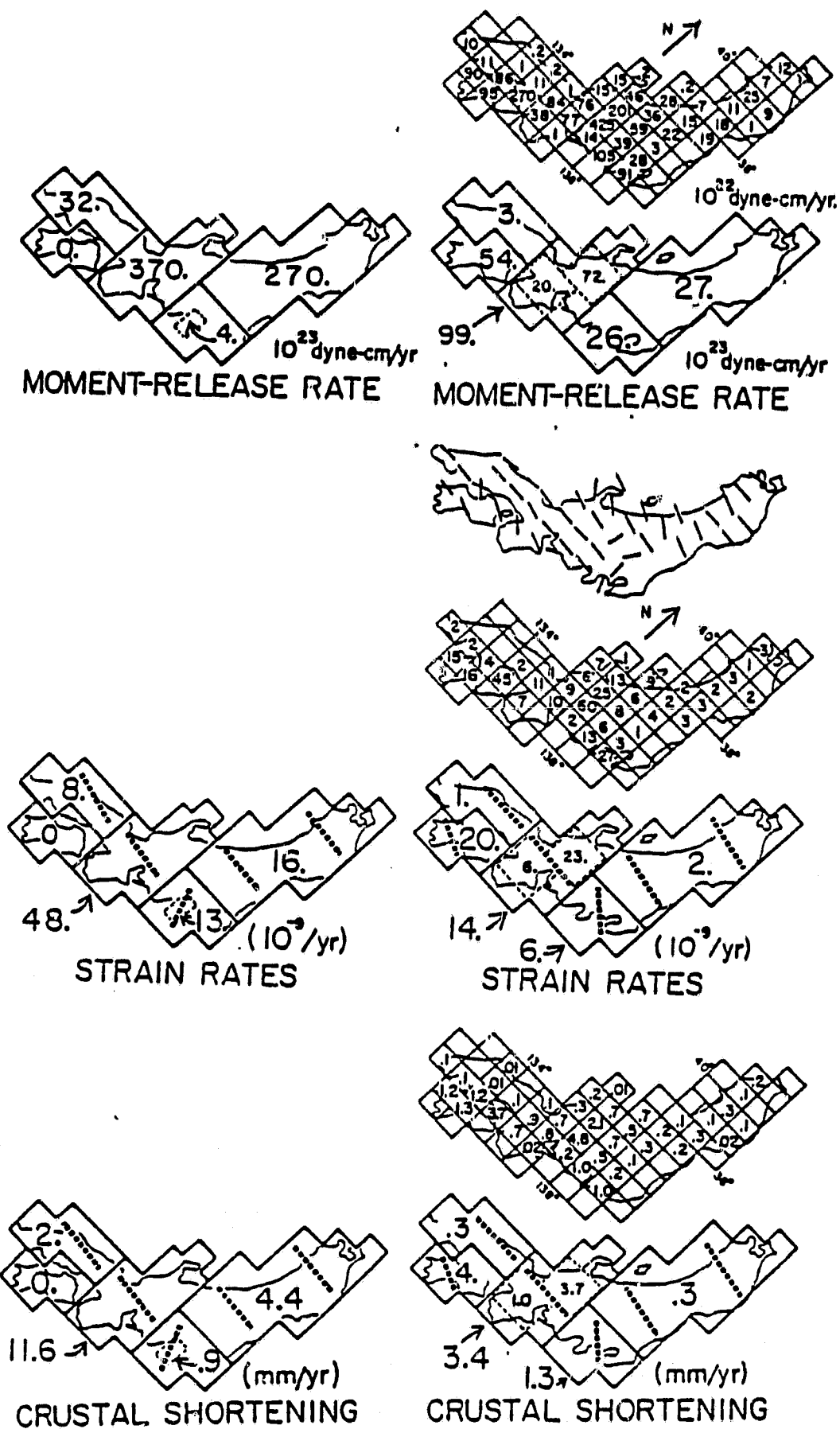


Figure 1

Figure 2

CONTINUING RESEARCH

Crustal Deformation in Alaska

The grant has partially supported transmission via satellite of geodetic data from two seismic gaps in Alaska. It has also aided the development of pressure recording systems used to detect long-term water level changes resulting from tectonic displacement of the earth. Seven 17 m long carbon-fiber strainmeters were installed in shallow surface sites near the coast of the Gulf of Alaska within the Yakataga seismic gap. All the instruments are located above the forecast rupture zone. Hourly-mean strain data are telemetered via the Landsat 3 satellite for analysis in New York.

Transmissions have been received from six of the strainmeters since November 1980. One transmitter and two strainmeters had early malfunctions and a third strainmeter ceased operation in January 1981. Three strainmeters continue to transmit data of good quality. The least-count resolution is approximately 10^{-9} strain.

The load tide signal has a maximum peak amplitude of 4×10^{-7} strain. Superimposed on the tidal signal are strain rates that vary from 10^{-8} /day lasting for as long as 30 days and strain rates of 5×10^{-7} /day lasting less than 5 days. The higher strain rates are probably associated with temperature, rainfall, and ground expansion during freezing processes. Our ability to distinguish tectonic signals amid these large atmospherically-induced strains depends on the magnitude and spatial geometry of likely precursory strainfields.

Since storm conditions are essentially synchronous across the Yakataga coastline, we cannot use temporal coherence alone to search for possible tectonic signals within the strain time series. In order that we may detect unambiguously a strain precursor, the magnitude of the precursory tectonic strain rate must either exceed the maximum observed strain-noise rate (e.g., 10^{-6} /day) or we must be able to distinguish the precursory strain signal from the noise by virtue of its spatial geometry. The nature of a short-term strain precursor to a magnitude 8.1-8.3 earthquake cannot be surmised from historical data since no continuous strain data from within the epicentral region of an event of this magnitude have been reported. Moreover, the spatial form of strainfields generated by fast-moving storms are likely to be difficult to predict. Because of the large size of strain precursors that have been reported for twenty out of forty documented precursory strain events (Bilham, 1981), we remain optimistic about our detection capability.

A newly designed sea-level instrument is to be installed in Alaskan seismic gaps in 1981 to monitor crustal movements associated with future seismicity. The device consists of two ceramic pressure gauges: one to monitor barometric variations and the other installed in shallow water on the coast to measure sea-level variations. The instruments have a resolution of approximately 1 mm over a range of more than 10 m. Sea-level, barometric pressure, and sea water temperatures will be averaged for 12 minutes, stored for up to three hours, and telemetered via the GOES satellite. In each region we will install two permanent gauges and one portable gauge. The portable gauge will be operated for variable lengths of time in order to estab-

lish several vertical-control points within and near each seismic gap. These control points will be reoccupied yearly.

Crustal Deformation in Iceland

The South Iceland Seismic Zone is an east-west trending zone of large historic earthquakes that transfers motion from the submarine Reykjanes spreading center to the Eastern Volcanic Zone in southern Iceland. Major earthquake sequences affecting most of the 70 km long zone recur at intervals of 50 to 100 years. Earthquakes of magnitude 7 or greater have been recorded. No major earthquake sequence has occurred since 1896, and the whole zone has had a low level of seismic activity instrumentally located in it for the past 50 years. Thus there is a high probability for the occurrence of a large earthquake in the zone in the next few decades. The grant has helped to initiate a program for installing 5 water level sensors in Lake Hestvatn, located in the center of the seismic zone. The lake surface is used as a reference level to measure crustal tilt in the area. Anomalously rapid tilting has been observed before earthquakes in some cases.

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